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Separation of edge detection and brightness perception

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Abstract

When a low spatial frequency noise mask is superimposed onto a luminance staircase, the perceived brightness pattern is dramatically altered although the edges remain visible. We measured contrast thresholds for the edges and for the illusory scalloping (Chevreul-illusion), as a function of noise center spatial frequency. The masking tuning functions overlapped, but peaked at different spatial frequencies and contrast levels. The results suggest that perceived brightness is triggered only by the low spatial frequency components of the edges—the high spatial frequency components are not able to produce a brightness pattern.

Keywords: Chevreul-illusion; Masking; Edge; Brightness; Filling-in

1. Introduction

The retino-geniculate pathway provides visual cortex with information about local luminance changes, i.e. local contrasts (Hubel & Wiesel, 1962). Since only local information is available, the properties of extended surfaces must also originate from local signals. For example, a classical assumption is that local edges somehow trigger brightness (Gerrits & Vendrik, 1970). In this paper we use the Chevreul-illusion to study the relationship between edge detection and brightness perception.

In 1839, chemist Michel Eugéne Chevreul observed that a simple luminance staircase consisting of homogenous stripes has a peculiar appearance: "We shall perceive that instead of exhibiting flat tints, each stripe appears of a tone gradually shaded (Chevreul, 1839/1981)" (Fig. 1). Current multi-scale brightness models explain the illusory perception in two different ways. Some models assume that the illusion arises because there are local features corresponding to the illusion (Kingdom & Moulden, 1992; Morrone, Burr, & Ross, 1994; Watt & Morgan, 1985)—the models detect edge- or bar-like features *within* the steps, not only at the step edges. Other models assume that the illusion reflects the properties of a filling-in process, the step edges being the only features detected in the stimulus (Pessoa, Mingolla, & Neumann, 1995). There, scalloping originates because the filling-in process is spatially decaying. The models suggesting local features assume that the illusion originates from the low spatial frequency component of the stimulus. The model assuming filling-in does not suggest any particular scale for the scalloping. Since in the model filling-in is triggered (and constrained) by the edge signals, a straight forward assumption would be that the scalloping arises from the same spatial scales that signal the step edges.

There are hardly any empirical studies on the Chevreul-illusion (Kusaka, 1982; von Békésy, 1968) and in particular, the spatial frequency specificity of the illusion has not been studied. More importantly, the spatial frequency specificity of edge detection and brightness perception have not been studied simultaneously. In this paper we inquired as to which spatial scale(s) contribute to the perceived scalloping and whether they coincide with the spatial scales underlying the performance in edge detection. We masked a luminance staircase with isotropic noise at different spatial frequency bands and measured the contrast thresholds for the perceived scalloping as well as for the step edges. Furthermore, to gain insight into the available versus utilized stimulus information, we filtered the stimulus with linear band-pass filters and correlated the filter output patterns with the measured masking tuning functions.

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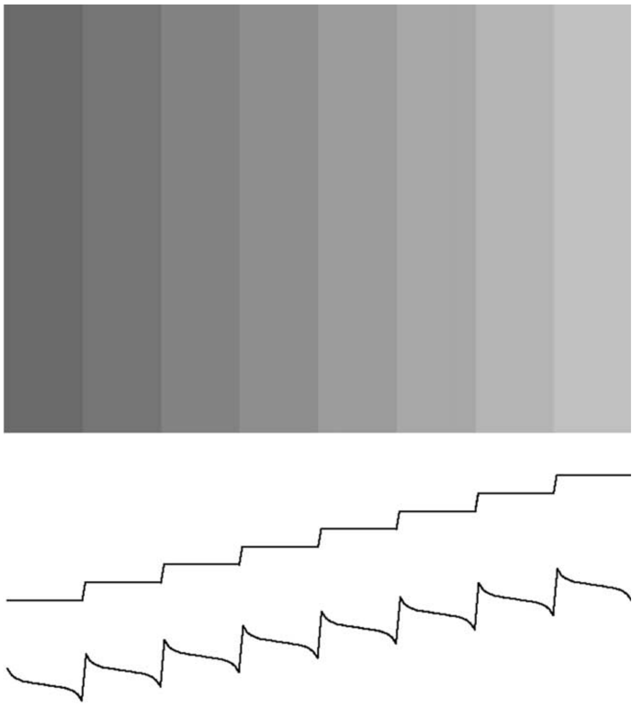

Fig. 1. The luminance staircase stimulus. The actual and perceived brightness distributions are depicted below the image.

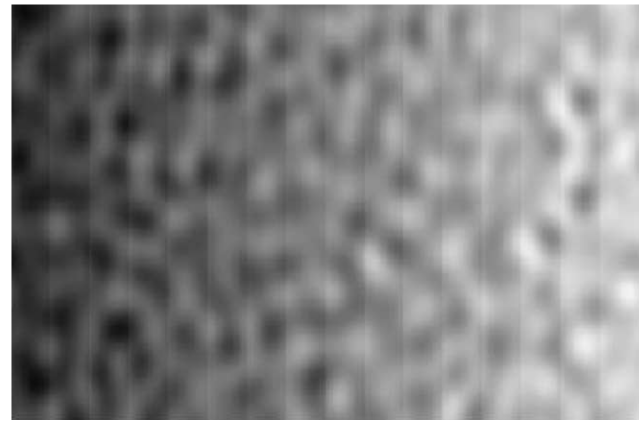

Fig. 2. An isotropic noise mask with a center frequency of 1 cycle/step superimposed onto the luminance staircase. The step edges are clearly visible, but scalloping is not.

2. Methods

2.1. Stimuli

The stimuli were generated and the experiments were run on a VisionWorks 3 system by Vision Research Graphics. Images were presented on a linearized 21″ color monitor (Eizo FX-E7S).

The stimulus was a luminance staircase with 15 step edges (i.e. 16 uniform steps). (We will use the term step edge here, rather than just edge, to avoid the confusion of physical edges and perceived edges.) The luminance of the steps increased by equal increments (in cd/m^2) from left to right, so that the mean luminance of the whole stimulus was equal to the mean luminance of the display (25 cd/m^2). The step edge contrast was defined as step magnitude/mean luminance. The maximum contrast available was 8.2%. From a viewing distance of 75 cm the stimulus size was $15.9° \times 8.1°$, step width 1°, and the uniform background subtended $23.9° \times 18.4°$. An isotropic bandpass noise mask was superimposed onto the luminance staircase (Fig. 2). The full bandwidth at half amplitude of the Gaussian amplitude spectrum was 1 oct. Eight different center spatial frequencies were used: 0.25, 0.5, 1, 1.5, 2, 3, 4 and 7.5 c/deg. The rms-contrast of the noise was 1.7%. A new noise sample was generated for each presentation of the stimulus. The superimposition of the luminance staircase and the noise mask was accomplished by presenting them in alternate frames of the video sequence at a rate above the flicker fusion frequency (frame rate 160 Hz).

2.2. Procedure

The method of constant stimuli was used to measure the contrast threshold for the perceived scalloping and for the step edges. The contrast of the step edges in the staircase was varied in 15 steps. The range of contrasts used (and consequently the contrast step size) was defined in a pilot study, individually for each subject. Luminance staircases with different step edge contrasts were presented 10 times in random order. The exposure duration was unlimited. The subject's task was to indicate, whether the scalloping or the step edges were visible or not. (We were forced to use a subjective method as the phenomenon to be measured is subjective by nature—c.f., Morrone et al., 1994; Morrone, Ross, Burr, & Owens, 1986.) The frequency-of-seeing was then calculated for each step contrast. The psychometric function (cumulative Gaussian) was estimated from the frequency-of-seeing data by maximum-likelihood method using the psignifit toolbox version 2.5.41 for Matlab (http://bootstrap-software.org/psignifit/, Wichmann & Hill, 2001a). The contrast threshold is defined as a frequency-of-seeing of 50%. The confidence intervals for the thresholds, corresponding to the cumulative probability levels of 0.16–0.84 were determined using an expanded, bias corrected bootstrap method (Wichmann & Hill, 2001b).

In a single session, the frequency-of-seeing as a function of contrast was measured for one mask spatial frequency and for one task. Thus, there were 18 sessions: 2 tasks × (8 mask center spatial frequencies + 1 unmasked condition). Contrast thresholds were plotted as a function of mask center spatial frequency. To estimate the peak spatial frequency and bandwidth of the masking tuning functions, log-normal Gaussian distribution was fitted to the contrast threshold data for each subject using the solver tool in Microsoft Excel 8.0.

2.3. Subjects

Four subjects, two (IK, AS) of which were naïve with respect to the purpose of the study participated in the experiments. All subjects had normal or corrected to normal vision.

2.4. Bandpass filtering

The (unmasked) stimulus was filtered with a bank of a quadrature pair of log-linear Gaussian bandpass filters, with the peak spatial frequency ranging from 0.1 to 10 c/deg in 1/3 oct steps. The frequency response was given by

$$R(\omega) = \exp\left\{ -\left(\frac{\log(\omega) - \log(P)}{q}\right)^2 \right\}, \qquad (1)$$

where ω is the spatial frequency and P is the peak spatial frequency and q is the space constant. The space constant q was defined as $[\log(2)]^{-1/2} * [\log(P) - P/\sqrt{2}]$ so that the bandwidth of the filter is 1 oct at half amplitude. The phase spectrum of the filters was constant at 0 rad (even filters) or at $\pi/2$ rad (odd filters). The filtering was implemented in a Matlab-environment. The positions (relative to the luminance staircase) of the peaks and troughs in the filter outputs were plotted as a function of filter spatial frequency (see du Buf & Fischer, 1995). A low threshold (2.5% of the step edge magnitude) was applied to the filter outputs before the peaks and troughs were located. The output magnitude was defined as the value of peak (trough).

3. Results

The masking tuning functions for the perceived scalloping and for the step edges were bandpass with bandwidths of 2.4 and 1.8 octaves, respectively (Fig. 3). The masking tuning function for scalloping peaked at lower spatial frequency than for the step edges (1.0 versus 1.9 cpd). The unmasked contrast threshold for perceived scalloping was higher than for step edges (1.9% and 0.95%, respectively)—in general, the scalloping was not visible at the threshold of the step edges, except for two of the subjects at the highest mask spatial frequencies.

Fig. 4A summarizes the multiple-scale pattern of filter outputs to the staircase stimulus. As expected, the step edge appears as peaks in the outputs of odd filters, located precisely at the position of the step edge for a wide range of filter spatial frequencies. Above ≈1 c/deg spatial frequency, the "side-lobes" of the step edge response (i.e. ringing) appears in the outputs of both odd and even filters. At low spatial frequencies the peaks and troughs are more stable, i.e. they occur in the same position over a range of spatial scales. The troughs in the outputs of odd filters are located at the center of the step. Around the same low spatial frequency range, the peaks in the outputs of even filters occur on the left side of each step, whereas the troughs occur on the right side. Fig. 4B shows the magnitudes of the stable peaks/troughs (marked with gray ellipses into 4A) as a function of the filter spatial frequency. Taken together, Fig. 4A and B indicate that in terms of filter outputs, the stimulus contains the following information: (1) Highpass odd response, above 0.3 c/deg with a local maximum around 1.15 c/deg, at the step edge location. (2) Bandpass 1 cpd/1.15 oct odd response, at the center of the step. The polarity is opposite to the step edge response. (3) Bandpass 0.6 oct even response below 1 c/deg—peaks at left side of the step and troughs at right side of the step. Notice that although we've analyzed the available stimulus information with rather narrow-band 1 oct filters, the exact bandwidth is not critical here—similar response pattern emerges also with 2 oct filters, only the bandwidths are slightly different.

In Fig. 5 normalized masking tuning functions for the two tasks are combined with the available stimulus information, as deduced from the pattern of filter outputs. The step edges (Fig. 5A) are bandpass masked around 1.9 cpd (black lines), representing only a narrow and relatively low spatial frequency slice of the highpass stimulus information (gray line). Perceived scalloping (Fig. 5B) is bandpass masked around 1 cpd (black lines); there is some individual variation between the subjects, though. In terms of stimulus information, masking occurs at the lowest spatial frequency component of the step edge response (gray line), i.e. around the fundamental spatial frequency of the periodicity of the staircase. Only at this spatial frequency range the filter outputs have a roughly sinusoidal shape—at higher spatial frequencies the shape is bi- or triphasic (see the profiles above the panels in Fig. 5). Also, only at this spatial frequency range there exist bandpass filter responses within each step—the odd center-of-step response (shaded area) as well as the even response on the left and right side of each step (not shown in the figure, for the sake of clarity). The bandwidth of the within-step filter responses is clearly narrower than the bandwidth of the masking tuning functions. However, direct comparison of the bandwidths is unfruitful, since the masking tuning function provides only a naïve estimate of the bandwidth of the underlying mechanism (Graham, 1989).

4. Discussion

We studied the relationship between edge detection and brightness perception by superimposing bandpass

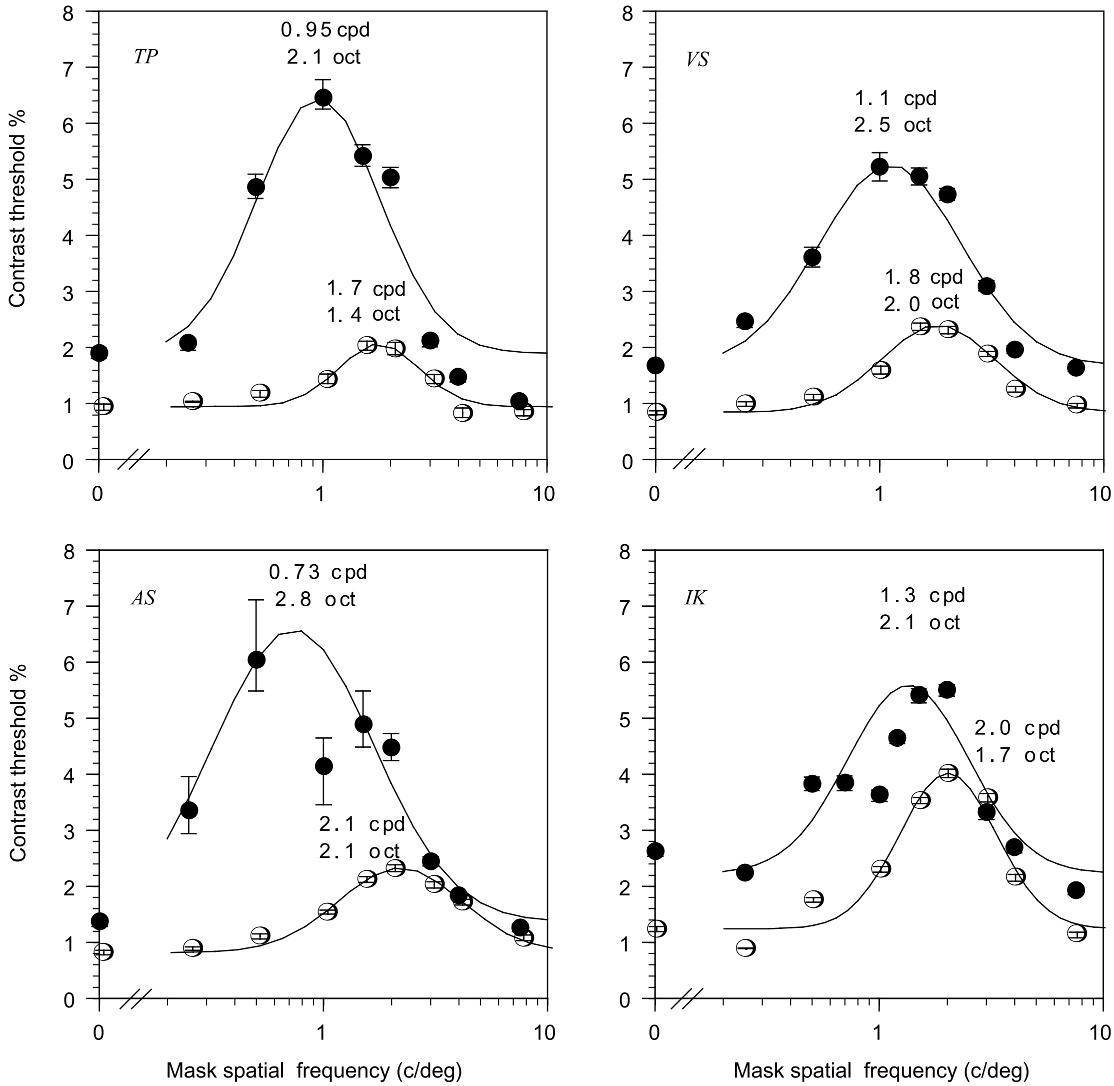

Fig. 3. The contrast thresholds for the perceived scalloping (●) and for the step edges (○), as a function of the mask spatial frequency. The unmasked contrast thresholds are plotted onto the ordinate. The error bars represent the cumulative probability levels of 0.159–0.841. The solid lines represent log-normal distribution fitted to the data points. The peaks and bandwidths presented above each curve are from the fitted distributions. The four panels show the different subjects.

noise onto the classical Chevreul staircase. The measured contrast thresholds for the visibility of step edges and scalloping were bandpass tuned, the tuning for scalloping peaking at lower spatial frequency than the tuning for step edges (1.0 and 1.9 cpd, respectively). Particularly, the visibility of the step edges was not a sufficient condition for the visibility of scalloping.

We will discuss the results from the two different modelling perspectives. First, however, we will consider the potential role of contrast sensitivity in determining the measured masking tuning functions.

4.1. The role of contrast sensitivity

The classical single-channel explanation of the Chevreul-illusion relies on the contrast sensitivity. Since a staircase can be considered as a combination of a sawtooth grating and a linear ramp, the insensitivity of the visual system to low spatial frequencies leads to the attenuation of the ramp, and accordingly, to the sawtooth-like appearance, i.e. scalloping (Cornsweet, 1970, p. 345). This approach, however, falsely predicts scalloping also into square-wave gratings—it has been shown that low spatial frequency square-wave gratings appear flat at all contrast levels (Campbell, Howell, & Johnstone, 1978; Sullivan & Georgeson, 1977). Neither can the CSF approach account for the suprathreshold appearance of the COC-illusion (Burr, 1987) nor the conditions under which Mach bands are visible (Morrone et al., 1986; Ross, Morrone, & Burr, 1989).

However, it is plausible that in the edge detection task the contrast thresholds are primarily determined by the

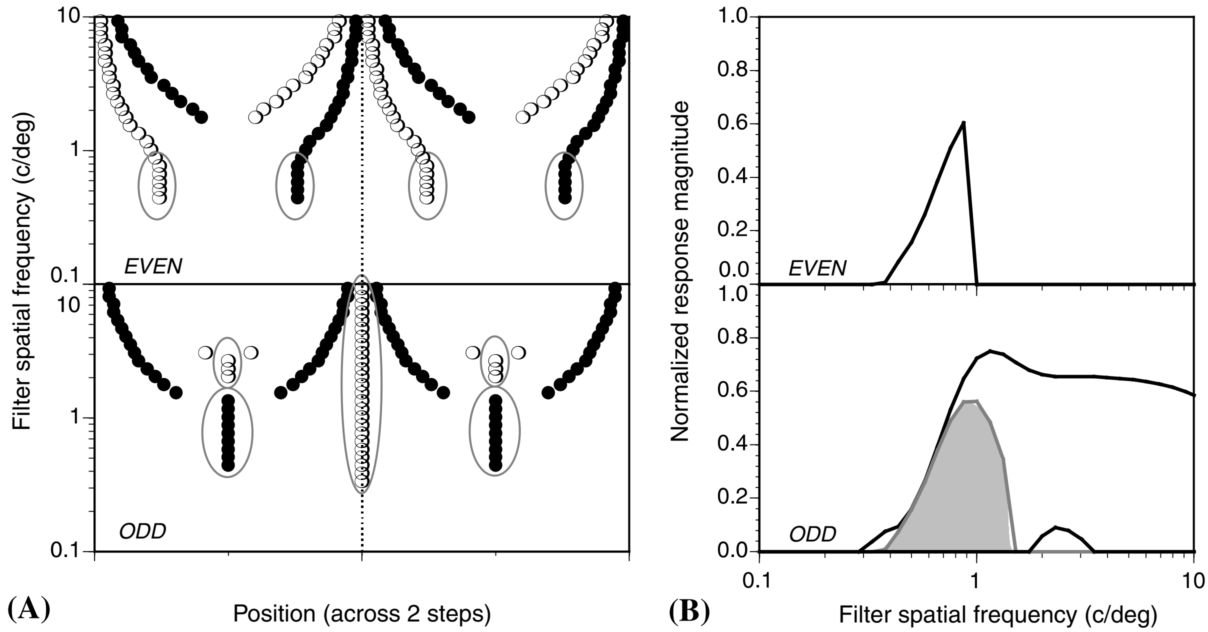

Fig. 4. (A) The pattern of filter outputs to a staircase stimulus. On the abscissa: the position in the stimulus across two steps (step edge location shown with dotted line), the ordinate: the center spatial frequency of the filter (c/deg). The top panels show the positions of peaks (○) and troughs (●) in the outputs of an even filter, and the bottom panels show the positions of peaks (○) and troughs (●) in the outputs of an odd filter. The gray ellipses indicate stable peaks/troughs. (B) Response magnitudes for the stable peaks/troughs as a function of filter spatial frequency, assuming step edge magnitude 1. The magnitudes of peaks are plotted with black lines and troughs with gray lines + shading. The top panel shows the response of the even filters (trough response is not shown because its magnitude is identical to the peak response). The bottom panel shows the response of the odd filters.

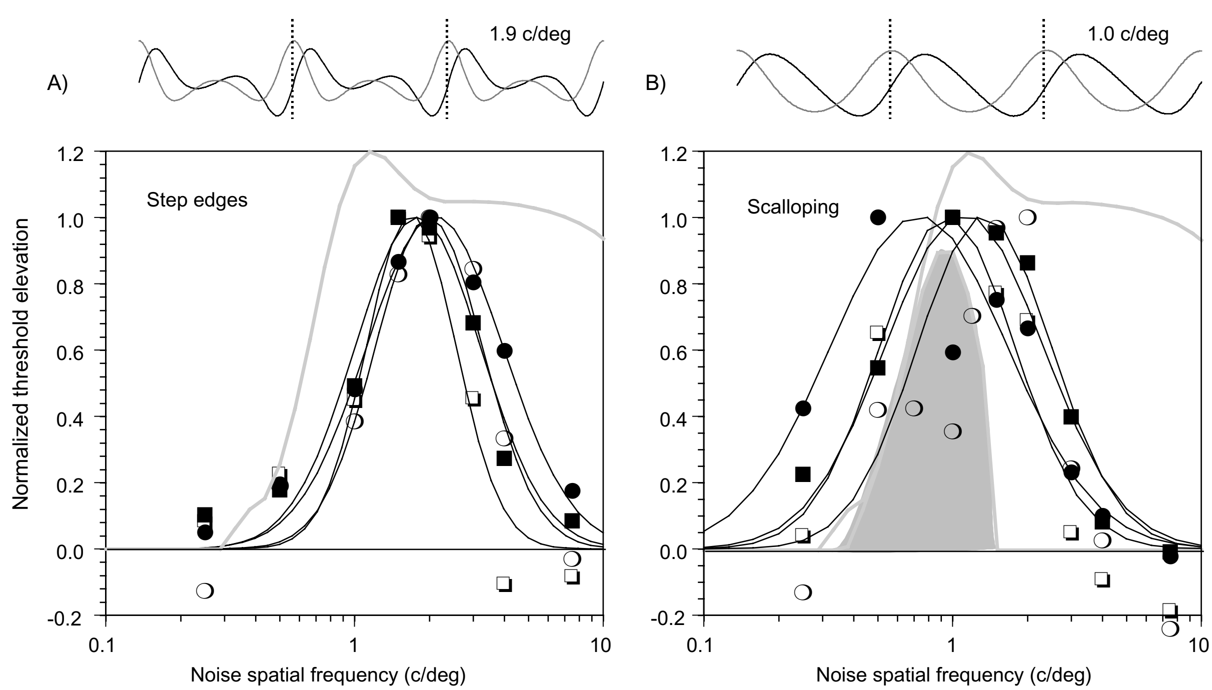

Fig. 5. Threshold elevation [(masked threshold – unmasked threshold)/unmasked threshold] scaled to unity as a function of the mask spatial frequency for the four subjects (TP (□), VS (■), AS (●), IK (○)). The two panels represent the two tasks: (A) step edges, (B) scalloping. The filter responses from Fig. 4B are plotted on to the figures with gray lines, with arbitrary scaling on the *y*-axis. Above the panels: even and odd filter output at the peak spatial frequency for each task. Step edge locations are marked with dotted lines.

channels with maximum response. The CSF measured for one of our subjects (AS) peaked at 2 cpd, very close to the 1.9 c/deg peak of the masking tuning function. Also, it has been shown that the tuning of the "edge detectors" revealed with the subthreshold summation technique (Kulikowski & King-Smith, 1973; Shapley & Tolhurst, 1973) can be explained with the available stimulus information if contrast sensitivity is taken into account (Graham, 1977; Hauske, Wolf, & Lupp, 1976; Jaschinski-Kruza & Cavonius, 1984). Assuming the role of CSF, the measured tuning is not in contradiction with the edge detection schemes in any of the brightness models.

4.2. Filling-in based explanation of the illusion

Pessoa et al. (1995) assume that scalloping originates from spatially decaying filling-in process, triggered by the edges at the different spatial scales. In our results, contrast thresholds for step edges were much lower than the thresholds for perceived scalloping, which would accord with this concept. Although the visibility of step edges and perceived scalloping did not exhibit identical spatial frequency tuning, the tuning functions partially overlapped, thus not actually contradicting the idea that scalloping arises from filling-in. However, in order to explain the scalloping as a product of filling-in, the triggering function of edges needs to be reconsidered. The low spatial frequency bandpass tuning of the perceived scalloping suggests that only low spatial frequency components of edges are able to trigger filling-in. Another possibility is that all spatial frequency components of the edges are capable of triggering filling-in, but for some reason the propagation fails in the presence of a low spatial frequency mask. However, this interpretation is unlikely because casual observations suggest that even without any mask, highpass filtered images do not possess a brightness pattern, only narrow edge or line like features.

4.3. Feature-based explanations of the illusion

Several models assume that local, low spatial frequency features within the steps signal the perceived scalloping (du Buf & Fischer, 1995; Kingdom & Moulden, 1992; Morrone et al., 1994; Watt & Morgan, 1985). However, the model by Watt and Morgan (1985) falsely predicts scalloping only into very narrow steps, the critical width being about 5 arc min, and the local energy model (Morrone et al., 1994) can explain only a modified version of the illusion, not the original one (Burr & Morrone, 1994; McArthur & Moulden, 1999; Pessoa et al., 1995).

In our results, the masking tuning function for the scalloping was bandpass, peaking around 1.0 cpd. At the center and sides of the steps the filter responses were also bandpass, peaking around 1 cpd and overlapping with the masking tuning function for scalloping. The overlap as well as the sinusoidal shape of the filter outputs at the critical spatial frequency range supports the idea of scalloping as a local feature—whether the features are identified on the basis of spatial coincidence of peaks and troughs of filter outputs (du Buf & Fischer, 1995) or on the basis of the shape of the filter output (Kingdom & Moulden, 1992), the relevant stimulus information lies at, and only at the spatial scale that signals the scalloping. In both models, the low spatial frequency features at the critical spatial frequency range produce a smooth, roughly sinusoidal brightness distribution more or less resembling the perceived brightness distribution of scalloping. Interestingly, in this particular situation, the filter output per se at the critical spatial frequency range resembles the perceived scalloping, even without the application of any classification rules. As the realistic bandwidth of the filters at the low spatial frequency range is about 2 oct (e.g. Wilson & Gelb, 1984), a single linear filter could probably directly signal the perceived scalloping. However, this kind of linear modelling of the illusion comes very close to the CSF-explanation and accordingly, shares the problems associated with it.

Although the perceived scalloping is well accounted for with the underlying features, the peculiar appearance of high spatial frequency, edge-type features requires some consideration. Fig. 2 demonstrates that when low spatial frequency part of the edges is masked, and only the higher spatial frequency components are left, the step edges appear as some sort of lines, not as brightness steps, as the underlying features would suggest. It would appear that high spatial frequency edges do not contribute to the brightness perception.

4.4. Conclusions

Taken together, our results indicate that the perceived scalloping in a Chevreul-staircase is well explained by the existence of local features within the steps. On the other hand, our results do not rule out the idea that the illusion arises from the filling-in process. Irrespective of the type of interpretation adopted, the results lead to a general conclusion about brightness processing: only low spatial frequency components of edges are able to trigger brightness filling-in or alternatively, symbolic interpretation of filter response as perceived edge—visible high spatial frequency components of edges do not produce a perceived brightness pattern, but possibly serve for other purposes, such as exact localization of the edges. Interestingly, also the apparent brightness of transparent surfaces seems to be mediated by low spatial frequency channels (Perna & Morrone, 2002).

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